Waste Biomass Valor (2012) 3:285–294
DOI 10.1007/s12649-012-9127-5

ORIGINAL PAPER

Evaluation of Pellets Produced with Undergrowth to be Used as Biofuel

N. L. Mustelier · M. F. Almeida · J. Cavalheiro · F. Castro

Received: 21 November 2011 / Accepted: 13 May 2012 / Published online: 12 June 2012
© Springer Science+Business Media B.V. 2012

Abstract Many European countries are developing the use of pellets or wood briquettes for the supplying of local energy. Many industries are being forced to replace fossil fuels with biomass because of its neutrality in relation to CO_2 emissions, thus creating an interesting market for pellets. In Portugal, the most common undergrowth includes: esteva (*Cistus ladanifer*), tojo (*Ulex europaeus*), giesta (*Sarothamus scoparius*), feto (*Pteridium aquilium*) and silva (*Rubus ulmifolius*). These undergrowth specimen are attractive due to the large volume available, but are not usually used for making pellets. It is possible to prevent large fires cleaning the forests, but this is an expensive task that could be compensated if the undergrowth can have some commercial value. The use of the common undergrowth for the manufacture of pellets and briquettes will allow the undergrowth to be considered not as a problem to be removed from the forest but an opportunity as renewable energy. The aim of this work is to obtain pellets with standard properties and evaluate the parameters that can qualify the performance of these pellets: moisture content, particle size distribution, high heating value, height of flame and burning time, pressure and temperature of the pelletizing process and mechanical durability. The pelletizing process was first simulated on laboratorial scale using small amounts of each vegetal specimen which was pressed in a heated mould. Some samples were submitted to a torrefaction treatment. After the laboratorial screening, the selected material was processed using a pellet mill to prepare pellets with 6 mm of diameter. The durability test was performed using a tumbling device following the ASAE S 269.4 standard. Burning tests of pellets with the same weight were performed and video images analysed, where height of flame and ignition time were measured. It was found that undergrowth pellets had good power of agglomeration and allow an easy ignition. The apparent density varies around 1,260 kg/m^3. The moisture content of different pellet varied between 2.79 and 7.46 %, ash content was less than 3 %, the calorific value is between 16 and 18 kJ/kg, the durability results respect the values recommended by standards. After ignition the flame increases to an average height of 25 mm. The total burning time was in all cases dominated by the cinder combustion without visible flame and the total complete burning time varied between 400 and 600 s. The results showed that it is possible to produce pellets of undergrowth with physical and thermochemical characteristics similar to the existing in the market at the present time.

Keywords Biomass · Undergrowth · Pellets · Biofuel

Introduction

Since the late seventies of the past century, the use of renewable sources for energy production has been encouraged and strongly divulged in Europe and in the United States of America. Nevertheless, nowadays, is Brazil that stands in a privileged position with regard to their primary sources of energy supply; it seems that the majority of the energy consumed in the country is originating from renewable energy sources (hydropower, biomass in the form of wood and wood derivatives such as

N. L. Mustelier (✉) · M. F. Almeida · J. Cavalheiro
Department of Metallurgy and Materials, Faculty of Engineering, University of Porto, Porto, Portugal
e-mail: niubis@fe.up.pt; niubis@yahoo.com

F. Castro
Centre for Waste Recovery (CVR), University of Minho, Guimarães, Portugal

sawdust, charcoal, derived from sugar cane and others) [1]. In this context, the production of energy from vegetable biomass constituted an important component, initially valuating the forest, agricultural residues and agro industrial already existing and subsequently giving more importance to the production of biomass for energy purposes. Many industries are being forced to replace fossil fuels with biomass because of its neutrality in relation to CO_2 emissions, thus creating an interesting market for pellets [2]. Due to its dimensional uniformity and thermal characteristics (>4.7 kWh/kg) the pellets may be used in boilers and automated heat exchangers, which regulate the burning in accordance with parameters previously entered in their control system. As such, it can be a regular energy supply process, suitable for space heating or water heating in household or industrial facilities [3].

The production of pellets using waste or residual materials has been reported by several authors: with straw/grass[4], pulp of olive [5], rice husks, coffee husks, bagasse from sugar cane [6], wood and wood waste [7], waste from industries in the second wood processing (furniture makers) [8]. Particle size distribution also influences the pelletizing performance. Large particles have a lower packing density than small ones and are less prone to block the dies [9, 10]. The basic properties of pellets such as moisture content, bulk and single pellet densities, compression strength and durability (abrasion resistance) depend on both the raw material composition and the pelletizing process variables [11, 12]. The moisture content of biomass fuels varies considerably, depending on the type of biomass and biomass storage. Increasing moisture content will reduce the maximum possible combustion temperature (the adiabatic combustion temperature) and increase the necessary residence time in the combustion chamber, thereby giving less room for preventing emissions as a result of incomplete combustion [13]. The nature of the combustion process depends both on the fuel properties and the combustion application. The combustion process can be divided into several general processes: drying, pyrolysis, gasification and combustion [14]. The gross calorific value (GCV) is defined as the heat released during combustion per mass unit of fuel under the constraints that the water formed during combustion is in liquid phase and that the water and the flue gas have the same temperatures as the temperature of the fuel prior to combustion. The GCV of biomass fuels usually varies between 18 and 22 MJ/kg (d.b.) [15].

Durability is defined as the ability of pellets to withstand destructive loads and force during transport, being the most important physical quality of a pellet [16].

There are many performance parameters and variables that influence the process of densification of biomass and the characteristics of the resulting product [17].

Torrefaction is a thermal pre-treatment technology performed at atmospheric pressure in the absence of oxygen. Temperatures between 200 and 300 °C are used, which produce a solid uniform product with very low moisture content and a high calorific value compared to fresh biomass [18].

In Portugal, a development program is being conducted for efficient exploitation of renewable energy resources. Great interest has been addressed to biomass, due to the large amount produced each year, especially residues from agricultural and agro-feeding industry. These are mainly cereal straw, olive-stone, and grape stone, whose utilization for energy production is very limited and confined to heat production.

The most common Portuguese undergrowth includes: esteva (*Cistus Ladanifer*), tojo (*Ulex Europaeus*), giesta (*Sarothamus Scoparius*), feto (*Pteridium aquilium*) and silva (*Rubus ulmifolius)*. This undergrowth invades the forest spaces and the absence of clean soil due to high costs greatly increases the risk of large-scale fires. These specimen are attractive due to the large volume available, but are not usually used for making pellets [19]. Unfortunately, for many reasons, one of which is the unknown physical and chemical properties of specific biomass as well as of the characteristics of the combustion and emission of pollutants associated to this type of fuels fundamental to the design and efficient operation of combustion systems.

The main objective of this study was to obtain pellets with standard properties and to investigate the various aspects of physical and thermochemical properties of pellets obtained from six varieties of undergrowth. These included moisture content, particle size distribution, high heating value, proximate analysis, ash composition, mechanical durability, height of flame and burning time. Some samples were submitted to a torrefaction treatment with the ultimate goal of improving energy efficiency and processing productivity and achieving higher heating values.

Materials and Experimental Procedure

Raw Materials: Proximate Analysis

Different Iberian species had been studied as: Feto, Giesta, Tojo, Silva and Esteva, more frequent species of undergrowth used in Portugal. The raw material was collected in the region of Serra do Caldeirão, Santa Justa and Pias, in the summer of 2010 (23/7), winter (15/1) and spring (05/05) 2011. During this process it was verified that different species have an annual cycle that allows a continuous supply of raw material for production of pellets. Being used for classifying the nomenclature presented in Table 1. The

Table 1 Symbols for and explanation of different raw materials

Vegetable residues	Nomenclature	
	Feedstock	Pellets
Feto—*P. aquilium*	F	PF
Giesta—*S. scoparius*	G	PG
Tojo—*U. europaeus*	T	PT
Silva—*R. ulmifolius*	S	PS
Esteva—*C. ladanifer*	E	PE
Commercial	C	PC

material was collected in the wild and fresh, stored in plastic bags.

All raw materials were dried at a temperature of 110 °C to constant mass and have been submitted to proximate analysis. Proximate analysis was performed on the biomass samples to determine the weight fractions of volatile, ash, and fixed carbon contents. The ASTM Standard Test Method for Proximate Analysis of Wood Charcoal (D 1762-82) [20] was used for vegetable residues.

The moisture content was determined by separating 500 g of sample of biomass with particle size less than 30 mm placed in an oven preheated at 105 °C and remained there until mass constancy.

The ash content was calculated using 1 g ± 0.01 of biomass, already without humidity and volatile, placed in a crucible inside a furnace with air influx at a temperature of 710 °C, and this condition was maintained for 1 h.

The volatile content was quantified by measuring the mass fraction of biomass that volatilizes during heating of a sample standardized and previously dried in an inert atmosphere, at the temperature of 850 °C in a muffle furnace for 7 min. The test procedures were applied to three samples of 100 g from raw material.

Then, the fixed carbon content was obtained by subtracting 100 % the sum of volatile matter and ash contents in percentage.

The determination of particle size distribution (% wt) was performed using calibrated sieves (Retsch) after the material was triturated in mill of knives with circular holes of 3 mm.

Three samples (5 g) from feedstock were selected to determine gross calorific value (GCV_0) by using a bomb calorimeter heat of oxygen according to the standard CEN/TS 14918:2005 [21].

Pelletizing Process and Pellets Characteristics

The pelletizing process was first simulated on laboratorial scale using small amounts of each vegetal specimen which was pressed in a heated mould. Some samples were submitted to a torrefaction treatment. After the laboratorial screening, the selected material was processed using a pellet mill to prepare pellets with 6 mm of diameter.

The drying temperature was 105 °C. The matrix was pre-heated to approx. 150 °C before processing and a pressure of 10 Kgf/cm^2. All samples were produced under the same laboratory conditions.

Pellets were produced without any additives. In a second simulation pellets were produced in industrial pelletizer at the Centre for Waste Recovery (CVR), University of Minho, pellets were obtained with identical results to the laboratory process. The characterizations performed on pellets untreated and torrefied are presented below:

Determination of Dimensions and Apparent Density

From each kind of samples 10 pellets were randomly selected for determination of single pellet density; each one of the pellets was measured weight, length and diameter. The volume and the average apparent density were calculated.

Determination of Moisture Content (w.b.)

The moisture content was measured by weighing a fuel sample about 100 g before and after drying at 103 ± 2 °C to a constant weight according to CEN/TS 14774-2 [22]. Three repetitions were used in each determination.

Determination of Ash Content (% dry wt)

The ash content was determined according to methods of loss on ignition at 550 °C based on the CENT/TS 14918:2005 standard [23] and was assessment 4 samples from each kind of pellets.

Determination of the Gross Calorific Value (MJ/kg)

Three samples from pellets and torrefied pellets (GCV), were selected to determine gross calorific value by using a bomb calorimeter heat of oxygen according to the standard CEN/TS 14918:2005 [21].

The Mechanical Durability

The mechanical durability was evaluated using tumbling device similar to the ASAE S 269.4 following CEN/TS 15210:2005 standard [24]. The rotation speed is fixed to 50 rpm for 10 min. In the test described here, a 100 g sample closed inside a box was tumbled for 500 rotations before being sieved manually with a 3.36 mm round hole sieve according to ISO 3310.2 [25]. The pellets used for this test were produced in industrial pelletizer at the Centre for Waste Recovery (CVR), University of Minho. The durability is expressed as the percentage in mass of the pellets remaining in the sieve to the total sample weight. It is calculated as the mean value of three replications and using the following formula:

$$\text{Durability} = \frac{\text{Mass of pellets after tumbling}}{\text{Mass of pellets before tumbling}} \times 100$$

Behaviour During Combustion and Torrefaction Process

Combustion

The pellets untreated were adjusted to a mass of 0.500 ± 0.001 g and a length of 8.0 ± 0.1 mm, depending on the initial pellet density (Table 3). To determine the time for the pyrolysis and char combustion phases respectively, single pellets were completely combusted. The characteristics of combustion were carried out with the aid of a small support burning manufactured by hand where the pellet is fully supported. We used a video camera and a background with a millimetric scale to monitor the various phenomena during combustion. This characterization process can still be improved in future investigations.

In this characterization we assessed the initial time of pyrolysis, flaming pyrolysis time and char combustion time as well as the curve of the flame behaviour and maximum height reached. In this study, the following definitions were used [26]:

- Drying and initial pyrolysis time is the time from the moment the pellet enters the support until the moment when a flame around the pellet becomes visible.
- Flaming pyrolysis time is the time a flame around the pellet is visible, i.e. combustion of volatilized pyrolysis gases.
- Char combustion time is the time from the moment when the flame around the pyrolyzing pellet disappears (simultaneously the solid particle starts to glow) until the particle stops glowing.

Chemical Analysis of Ashes Calcium, magnesium, silicon and potassium are the main ash forming elements in untreated pellets and were obtained by atomic absorption spectrometry following CENT/TS 15290:2006 [27].

Torrefaction

Torrefaction is a treatment which serves to improve the properties of biomass in relation to thermochemical processing techniques for energy generation; for example, combustion, co-combustion with coal or gasification and they are still in the pilot stage of production in other countries. The pilot process was conducted in a tube furnace with a heating temperature up to 230 °C for 30 min, after which it was made a stage for 30 min at this temperature. A nitrogen flow of 0, 34 cm^3/min was used to avoid combustion of the biomass. An inflamed lamp with the flame is placed in the exit extremity of the gases to guarantee their burning. The cooling of the biomass is made naturally inside the tube.

In order to study the thermal behaviour of these solid biofuels were made the weight loss curves (TGA), under an inert atmosphere (argon). During thermo gravimetric analyses a heating rate of 10 °C min was used up to 250 °C in order to obtain the profiles of the process of torrefaction. From each sample we used a representative mass of 600 mg, dried at a temperature of 60 ± 10 °C, manually crushed in a ball mill and sieved in 150 μm, being used to test the material passing this sieve.

Morphological and Microstructural Characterization of Surfaces (SEM) The micrographs were taken using a scanning electron microscope (JEOL JSM 6301F) with the objective of verifying the surface topography and composition of untreated and torrefied pellets, as well as the impact of torrefaction on the surface of vegetables residues.

Results and Discussion

The results of the analysis of densified biomass untreated and torrefied tested were summarized in Tables 2 and 3, and discussed in the subsections below.

Raw Materials: Proximate Analysis

Table 2 shows the proximate analysis results. All the moisture content was high, with the exception of Esteva. The species presented high volatile matter content between 66 and 78 %. The ash content varies between 3.3 and 4.3 %. Fixed carbon content of 30.3 % of Feto is quite different from Giesta with 16.8 %. Gross calorific values of all of the species are similar, around 18 MJ/kg.

In this evaluation it was verified that the vegetable residues in nature present high volatile matter content, which is more than 66 %. The quantity of volatiles in biomass fuels is high and usually varies between 76 and 86 wt% (d.b.) in woody biomass [28]. This high proportion of volatiles results in most r part of the biomass fuel being vaporised before homogeneous gas-phase combustion reactions take place. The remaining char undergoes heterogeneous combustion reactions. Char oxidation lasts considerably longer than the oxidation of combustible gases during the combustion process. Therefore, the amount of volatile matter strongly influences the thermal decomposition and combustion behaviour of solid fuels [29]. This

Table 2 Proximate analysis of biomass

Proximate analysis	Biomass—Vegetal residues					
	F	G	T	S	E	Avg SD
Moisture (% wb)	51.17	46.06	45.95	50.71	12.60	0.6
Ash (% dry wt)	3.46	4.36	3.27	3.46	3.52	0.7
Volatile matter (% dry wt)	66.28	78.84	73.20	74.98	71.92	0.4
Fixed carbon (% dry wt)	30.26	16.80	23.52	21.57	24.56	0.6
Gross calorific value (MJ/kg)—GCV_0	18.76	19.35	18.47	17.82	18.63	0.4

Average of three replicates

Table 3 Quality parameter of pellets

Sample	Moisture content		Ash content		Gross calorific value (GCV)		Density		Length		Durability	
	(% wt)		(% dry wt)		(MJ/kg)		(kg/m^3)		(mm)		(<3 mm % wt)	
		**		**		**		**		**		**
PF	7.46	1.38	1.33	1.69	16.16	21.71	1,018.44	956.42	9.57	8.67	98.10	96.50
PG	2.79	1.55	1.57	1.74	17.44	21.42	1,274.48	962.80	11.83	9.33	97.07	94.50
PT	6.05	1.25	2.83	1.88	16.08	20.45	1,259.69	1,096.00	10.14	8.17	98.43	97.00
PS	4.14	0.08	2.71	1.62	16.40	20.19	1,252.72	1,174.03	10.50	8.17	98.50	97.05
PE	5.39	1.38	2.27	2.66	16.51	20.65	1,266.01	1,187.82	10.33	10.33	99.37	96.46
AVG (SD)	0.46	0.17	0.20	0.39	0.06	0.04	5.60	8.42	1.02	0.96	0.68	0.15

** Pellets with torrefaction

can be observed in n the results obtained with feedstock Giesta.

The results for determination of the particle size and the distribution were shown in Fig. 1. The particle size distribution for all species was similar and with size recommended by small scale pellet furnace manufacturer. Only the Giesta presented a discontinuity in the distribution, with 15 % of the material retained in the 3 mm sieve but with 75 % fine particles less than 0.85 mm. The particles size as well as distribution influence in the combustion behaviour of pellets. The development of automatic biomass heating systems with performance similar to oil or gas fired heating systems was only possible because of market introduction of pellets with uniform size and shape [30].

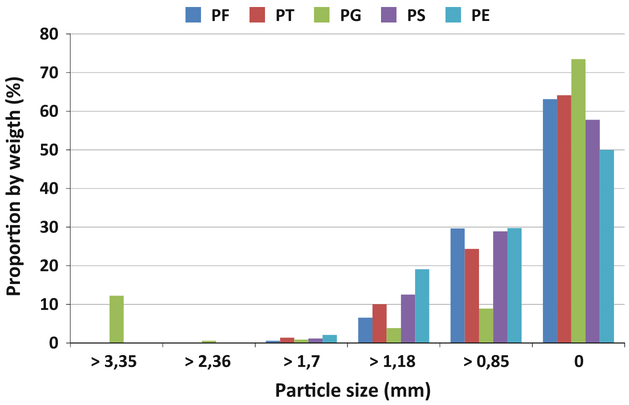

Fig. 1 Raw material particle size distribution

Pellets Characteristics

The produced pellets had 6, 8 e 10 mm of diameter but for the different characterizations carried out only the 6 mm pellets were used. The diameter of these pellets was in the range of 5.8 to–6 mm, and the length varies from 9 to 12 mm. The apparent density of pellets ranged between 1,274 and 1,018 kg/m^3 (see Table 3). The pellets PG, PT, PS and PE have similar densities with the denser pellets PF. A guiding value $\geq$600 kg/m^3 for the apparent density of wood pellets is specified in the Swedish standard. The results showed that the apparent densities of the samples were found above this value. Visual observations allow to verify that the laboratorial pellets were well compacted but they presented better aspect if the time of permanence in the matrix during the production process was prolonged. This was also verified in another work [31].

The moisture content of solid biomass influences the calorific value and the combustion efficiency. The guiding value from ÖNORM M 7135 and DIN plus is below 10 %, while DIN 51731 states the moisture content should be below 12 % [32–34]. The average moisture content of commercially produced pellets varies between 10 and 12 %. All the pellets produced in the different species showed values ranging from standard established varying of 2.79 to 7.46 %. It is important to note, that these values are due to the fact that the samples have been characterized 1 month after produced (Table 3).

The results obtained for the pellets produced with torrefaction show that the content moisture was considerably reduced, when compared with untreated pellets. The moisture content of torrefied biomass was very limited by standard, varying from 1 to 6 %. The moisture content of torrefied biomass was very limited due to the dehydration reactions during the torrefaction reaction. Destruction of OH groups in the biomass by dehydration reactions causes the loss of capacity to form hydrogen bonds with water. In addition, non-polar unsaturated structures are formed which makes the torrefied biomass hydrophobic [35].

The ash content in biomass was highly variable. On Table 3 can be observed that is possible to attribute a typical range of the ash content of the biomass originated from undergrowth, with a small variation of the ash content in each type of biomass. The pellets produced with Feto and Giesta presented smaller values compared to the pellets produced with the Tojo that presented higher values (around 2.83 %). The high values can be explained primarily by mineral impurities present in the bush stems that are strongly projected to the upper leaves during heavy rains which can contribute to increase ash contents. During burning the presence of high levels of ash originates normally high emission of particles and formation of slags that clogs the burning systems.

In order to maintain a high operating comfort for end users in the residential heating sector, high ash content must be avoided [36]. According to results, ash content was inside acceptable limits (1–3 % for normal quality) and the torrefied pellets present ash content 50 % lower than untreated pellets, which means that the contaminating inorganic particles can be separated during the manipulation of the torrefied material.

The differences in the values of gross calorific value, dry basis, found among the tested biomass samples, ranged from 16.08 and 17.44 MJ/kg (variation 3.6 %). These values are interesting and sufficiently high to justify the use of a waste energy plant. The small variation between the values of the GCV also indicates that other species of biomass plant. The values of GCV may be within this range.

The PG pellets had the highest gross calorific value of all the pellets tested, probably due to the highest values of volatile matters present in the raw materials. The ash content can be seen in Fig. 2. Torrefied pellets showed higher calorific value, ranging from 20 to 22 MJ/kg due to the fact that during torrefaction, biomass loses relatively more oxygen and hydrogen compared to carbon. Subsequently, the calorific value of the product increases.

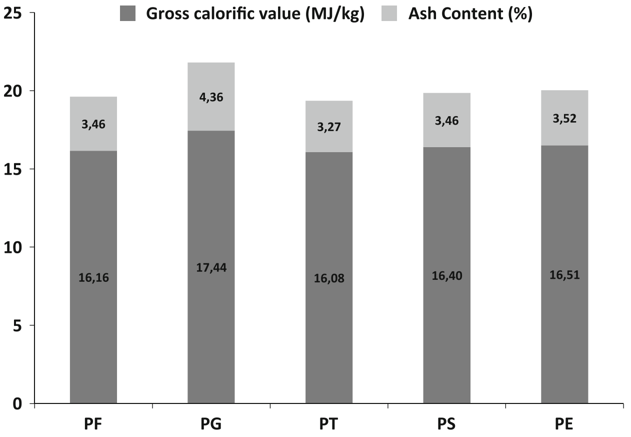

Fig. 2 Gross calorific value and ash content in the different pellets untreated

According to Table 3, all biomass pellets had a durability value above 97.5 %, indicating that the pellets were very durable. Among the five types of biomass, pellets PG had the lowest durability value. Low pellet durability is not desirable as it can cause problems during transport and with pellet feeding systems, increasing dust emissions, and an increased risk of fire explosion during pellet handling and storage. Regarding the durability of the torrefied pellets it was found that the value is not enough to achieve the standard levels (higher than 97.5 %).The torrefied biomass also becomes more porous with a volumetric density of 956–1,100 kg/m^3. It is more fragile as it loses its mechanical strength, making it easier to grind or pulverize.

Performance During Combustion and Torrefaction Process

Combustion

The conversion times during the combustion of the pellets produced with undergrowth is shown in Fig. 3. The total

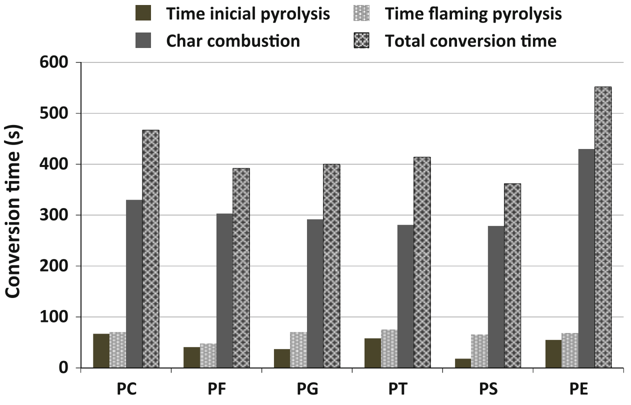

Fig. 3 Comparison of conversion times during the combustion of the untreated pellet

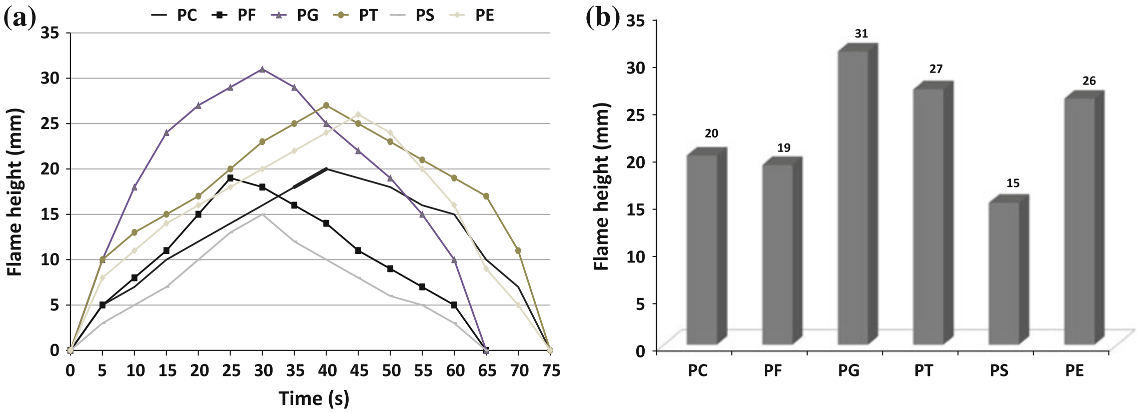

Fig. 4 Behaviour of the flame during pyrolysis of the pellet untreated. **a** Curve evolution, **b** the maximum height reached

conversion time was in all species dominated by the char combustion phase.

After initial smoldering for nearly 1 min, the pellets started to burn, lasting for 1.5 min with flame. The incandescence lasted for 4 to 7 min. This behaviour is due to the overlap of devolatilization and char combustion, where the volatiles burn as gas products, whereas the fixed carbon burns slowly [37, 38]. Among all, the PE pellets had the best time of combustion and a more complete combustion during the visual information. Regarding the curve behaviour of the flame, a common behaviour can be observed, with an increase to reach the peak that gradually decreased as shown in Fig. 4. The length of the flame was initially 25 cm high and decreased continuously until it died down. Except for a few traces of smoke observed initially, the samples burned without smoke. The greater height of flame was reached by PG pellets, which exhibited the higher volatile content, while PS pellets exhibited the lowest height of flame but had also a high volatile content, as it can be observed in Fig. 4.

Chemical Analysis of Ashes Si, Ca, Mg, Na and P are the major ash-forming elements occurring in biomass fuels being present in biomass in the form of oxides. Their concentration ranges are shown in Table 4.

The highest concentrations typically present in the species studied are Si, P, and Ca. In general, the levels are set upon by the standard. The sulphur content in the samples investigated has been detected to vary between 2.4 and 1.25 % and the chlorine content varies between 1.72 and 6.86 %. Increaæsed concentrations of the elements Cl and S can be the result of a chemical contamination by, e.g. insecticides, adhesives, glues, lacquer, dyestuff or wood preservatives in the raw material or a result of the use of additives. The concentrations of these elements should be limited due to their negative influences on the combustion process. High amounts of S and Cl can cause problems regarding emissions (HCl and SOx), deposit formation and corrosion. Furthermore, Cl influences the formation of dioxins and furans (PCDD/F). Minor ash-forming elements occurring in various biomass fuels are Fe, Al, and heavy metals.

Table 4 Chemical compounds present in the ashes of different kinds of pellets evaluated and commercial briquettes and pellets

Pellets	Average of the chemical compounds (%)											
	SiO_2	Fe_2O_3	P_2O_5	Al_2O_3	CaO	MgO	SO_3	Na_2O	CuO	C	S	Cl
PF	24.00	0.53	7.97	0.91	15.50	6.86	4.75	2.47	0.02	4.10	1.90	6.86
PG	0.02	2.38	11.90	5.34	22.40	7.65	5.25	8.90	0.08	3.40	2.10	3.05
PT	14.10	2.72	6.07	8.16	16.40	8.71	6.00	10.70	0.06	3.90	2.40	3.71
PS	3.27	0.86	8.31	1.89	46.30	9.33	3.13	1.12	0.02	7.60	1.25	1.30
PE	4.06	1.15	8.72	2.45	41.30	9.99	3.60	0.86	0.03	6.90	1.45	1.72
PC_1	3.86	2.06	1.08	1.47	16.40	3.52	0.38	1.31	0.03	62.10	0.15	0.03
PC_2	9.07	3.28	2.09	4.73	17.20	5.59	0.80	1.35	0.02	48.70	0.32	0.06
BC	33.50	2.90	1.85	4.52	38.30	2.67	1.30	0.44	0.01	6.10	0.52	1.08

Average of the chemical compounds (%)

PC_1 PC_2, commercial pellets; BC, commercial briquettes

Torrefaction Process and Torrefied Pellets

In Fig. 5, TGA (thermo gravimetric analysis) experiments with five vegetables species are shown. To view all the curves was performed a shift of 5 °C for each one from the BF. The gravimetric yield of all the curves start at 100 %. As can be seen during torrefaction process a large part of the initial mass of fuel was preserved, recovering 80 % of the initial energy of the raw material. Torrefied biomass typically contains 70 % of its initial weight and 90 % of the original energy content [39, 40]. The five species show similar trends for weight loss during the heating process being presented only one of the curves of the species.

Torrefaction process has different stages: the initial heating, pre-drying, post-drying and intermediate heating stages. It is clearly noticed that four stages are present for all species analyzed. The figure shows that the mass yield of torrefied biomass decreased with increase in torrefaction temperature. The first peak before 100 °C is probably physically adsorbed water, while the decomposition is attributed to other gaseous compounds. The mass yield started to decline dramatically from temperature of 250 °C and became only about one-half of the original weight when torrefied temperature reached 250 °C. The mass loss was primarily due to thermal decomposition of hemi-cellulose and some short chain lignin compounds [41]. The decomposed volatiles can be captured and used for various applications. Table 5 shows the gravimetric yield and the various energy indices. Comparing the results between product and torrefied charcoal, it was noted that the conversion efficiency is significantly higher in the torrefaction, tripling the yield of charcoal.

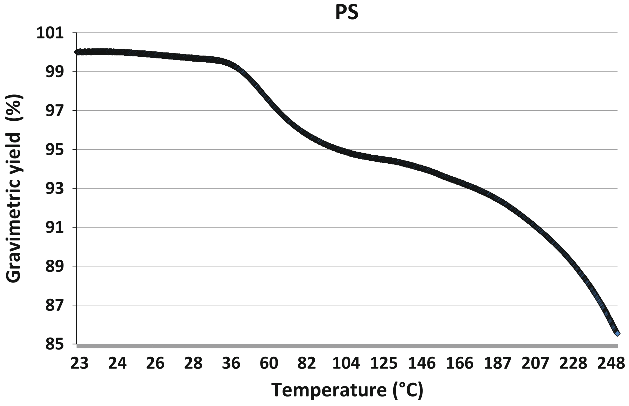

Fig. 5 Thermogravimetric profile of the torrefaction process of one specimen

Morphological and Microstructural Characterization of Surfaces Observation Figure 6 shows the images obtained by scanning electron microscope (SEM). In order to verify the structure and morphology of the untreated pellets and after undergoing the process of torrefaction.

It can be seen that the untreated pellets have a mixed and heterogeneous morphology, with structures like tubular-shaped filaments with small particles on surfaces, in contrast with the images of torrefied pellets, where more consistent and compact structures can be observed. According to the images of the pellets with torrefaction, the impact of torrefaction in the surfaces of vegetable residues is not aggressive and seems to be favourable for obtaining structures more cohesive and uniform.

Conclusions

In this study, we obtained data on the properties of five varieties of vegetable residues pellets (i.e., esteva (*C. ladanifer*), tojo (*U. europaeus*), giesta (*S. scoparius*), feto (*P. aquilium*) and silva (*R. ulmifolius*).The results showed that it is possible to produce pellets of undergrowth with physical and thermochemical characteristics similar to the

Table 5 Conversion yield and energy indices

Pellets	Gravimetric yield (%)[a]	GCV_0 (MJ/kg)	GCV (MJ/kg)	GCV/ GCV_0	Density (kg/m^3)	Energy recovery (%)[b]	Density energetic (10^{-6} kJ m^{-3})[c]
PF	90.43	18.76	21.71	1.16	956.42	104.65	20.77
PG	91.05	19.44	21.42	1.10	962.80	100.29	20.62
PT	92.18	18.50	20.45	1.11	1,096.00	101.89	22.41
PS	90.03	17.82	20.19	1.13	1,174.03	101.99	23.70
PE	87.59	18.63	20.65	1.11	1,187.82	97.07	24.52
CV	27.00	31.08		1.78	250.00	48.06	7.77

CV charcoal

[a] Obtained from the gravimetric difference in the range 100–250 °C—Fig. 5

[b] Energy recovery is calculated by: (GCV/GCV0) (% Gravimetric yield)

[c] Density energetic is calculated by: (density × GCV)/1,000

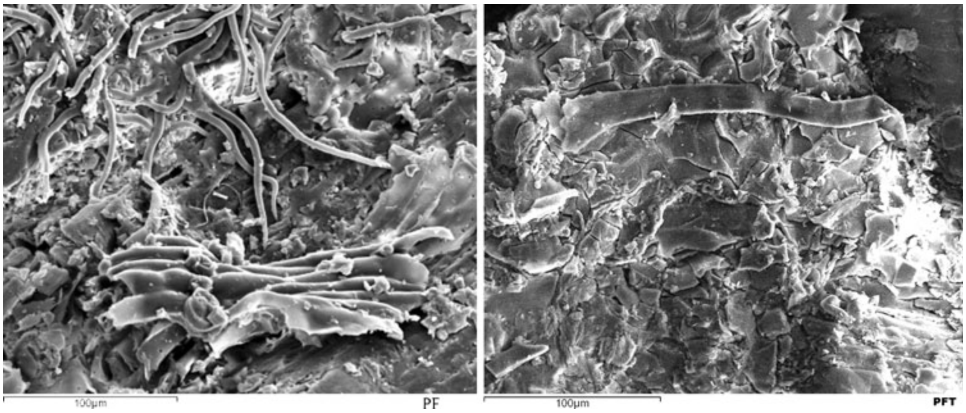

Fig. 6 SEM images of untreated pellet (*left*) and torrefied pellet (*right*) (torrefaction temperatures = 250 °C/ time = 1 h/particle size >100 µm). Feto (*P. aquilium*)

existing in the market at the present. Apparent density ranged from 86 to 114 kg/m^3. Volatile matter contents were more than 66 % (dry basis) for all samples. The biomass of vegetable waste from the undergrowth, presented thermochemical characteristics appropriate for its use of energy. The pellet showed up strong and durable with high density which made them easier to handle, transport and store.

During torrefaction various permanent gases and condensable, with high oxygen content, are formed mainly due to hemicellulose degradation. As a consequence the final solid product, so called torrefied biomass, will be composed mainly of cellulose and lignin and characterized by increased brittleness, hydrophobicity, microbial degradation resistance, and energy density. Densification of torrefied vegetables residues is easy through a pelletization process. Probably due to a higher content of lignin and fatty unsaturated structures in torrefied biomass, high density pellets of 1,187.82–956.42 kg/m^3 can be produced from torrefied biomass. However, pellets with a torrefaction need further study regarding the binders in order to improve its durability.

Physical and fuel characteristics of torrefied biomass were superior compared to that of untreated biomass. More research is needed on the effects of raw material characteristics, seasonal variations, collection and storage of raw material as well as manufacturing process in order to design a production line which would produce pellets with the required quality established by norms while considering the specific application of pellets. Finally the use of undergrowth to produce heating pellets can be an important contribution to introduce the undergrowth in the value chain with positive effects on the economy of forest and fire prevention.

Acknowledgments This research is part of the results obtained in PTDC/AGR-AAM/104288/2008 project funded by the Foundation of Science and Technology, Portugal and support of the COMPETE.

References

1. Barreto, E.J., Rendeiro, G., Nogueira, M.: Combustion and Gasification of Solid Biomass: Energy Solutions for the Amazon. Ministério de Minas e Energia, Brasilia (2008) (in Portuguese)
2. Junginger, M., Bolkesjø, T., Bradley, D., Dolzan, P., Faaij, A., Heinimisö, J., et al.: Developments in international bioenergy trade. Biomass Bioenergy **32**(8), 717–729 (2008)
3. Cavalheiro, J.: How to Introduce Biomass for Economic Circuit. Guimarães, Centre for Waste Recovery (2010) (in Portuguese)
4. Kaliyan, N., Morey, R.: Densification characteristics of corn Stover and switch grass. Am. Soc. Agric. Biol. Eng. **52**(3), 907–920 (2009)
5. Al-Widyan, M.I., Al-Jilal, H.F., Abu-Zreig, M.M., Abu-Hamdeh, N.H.: Physical durability and stability of olive cake briquettes. Can. Biosyst. Eng. **443**, 41–45 (2002)
6. Granada, E., López González, L.M., Míguez, J.L., Moran, J.: Fuel lignocellulosic briquettes, die design and products study. Renewable Energy **27**, 561–573 (2002)
7. Suárez, J.A., Luengo, C.A., Felfli, F.F., Bezzon, G., Beatón, P.A.: Thermochemical properties of Cuban biomass. Energy Sources **22**, 851–857 (2000)
8. Shaw, M.: Feedstock and Process Variables Influencing Biomass Densification. M.Sc. Thesis. Department Agricultural Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada (2008)
9. Holm, J.K., Henriksen, U.B., Hustad, J.E., Sorensen, L.H.: Toward an understanding of controlling parameters in softwood and hardwood pellets production. Energy Fuels **20**, 2686–2694 (2006)
10. Mani, S., Tabil, L.G., Sokhansanj, S.: Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenergy **30**, 648–654 (2006)
11. Rhén, C., Gref, R., Sjöström, M., Wästerlund, I.: Effects of raw material moisture content, densification pressure and temperature on some properties of Norway spruce pellets. Fuel Process. Technol. **87**, 11–16 (2005)
12. Lehtikangas, P.: Quality properties of pelletised saw dust, logging residues and bark. Biomass Bioenergy **20**, 351–360 (2001)
13. Gilbert, P., Ryu, C., Sharifi, V., Swithenbank, J.: Effect of process parameters on pelletisation of herbaceous crops. Fuel **88**, 1491–1497 (2009)
14. Van Loo, S., Koppejan, J.: The Handbook of Biomass Combustion and Co-firing. Earthscan, London, Washington DC (2008)
15. Obernberger, I., Thek, G.: The Pellet Handbook: The Production and Thermal Utilisation of Pellets. Earthscan, London (2010)

16. Tabil, L., Sokhansanj, S.: Process conditions affecting the physical quality of alfalfa pellets. Appl. Eng. Agric. **12**(3), 345–350 (1996)
17. Stelte, W., Holm, J.K., Sanadi, A.R., Barsberg, S., Ahrenfeldt, J., Henriksen, U.B.: Fuel pellets from biomass: the importance of the pelletizing pressure and its dependency on the processing conditions. Fuel **90**, 3285–3290 (2011)
18. Prins, M.J.: Thermodynamic Analysis of Biomass Gasification and Torrefaction. Ph.D. Thesis, Eindhoven Technical University, The Netherlands (2005)
19. Brás, A.M., Miranda, F., Hipólito, L., Dias, L.S.: Biomassa e produção de energia. http://www.draedm.minagricultura.pt/draedm/centrodocumentacao/revista_pdf/06.Biomassa_AldaBr%C3%A1s.pdf [29/09/2010]
20. ASTM: Standard Test Methods for Proximate Analysis of Wood Charcoal. ASTM, USA (1982)
21. CEN/TS 14918: Solid Biofuels—Method for the Determination of Calorific Value. British Standards, p.66 (2005)
22. CEN/TS 14774-2: Solid Biofuels—Methods for the Determination of Moisture Content. Oven Dry Method. Part 2: Total Moisture. Simplified Method, British Standards, p.12 (2004)
23. CEN/TS 14775: Solid Biofuels—Method for the Determination of Ash Content. British Standards, p. 12 (2004)
24. CEN/TS 15210: Solid Biofuels—Determination of Mechanical Durability of Pellets and Briquettes. Part 2: Briquettes. British Standards, p. 12 (2005)
25. Temmerman, M., Rabier, F., Jensen, P.D., Hartmann, H., Böhm, T.: Comparative study of durability test methods for pellets and briquettes. Biomass Bioenergy **30**, 964–972 (2006)
26. Obernberger, I., Thek, G.: Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass Bioenergy **27**, 653–669 (2004)
27. CENT/TS 15290: Solid Biofuels—Determination of Major Elements. British Standards, p.16 (2006)
28. Bergström, D., Israelsson, S., Öhman, M., Dahlqvist, S., Grefa, R., Boman, Ch., Wästerlund, I.: Effects of raw material particle size distribution on the characteristics of Scots pine sawdust fuel pellets. Fuel Process. Technol. **89**, 1324–1329 (2008)
29. Larson, T.V., Koenig, J.Q.: Wood smoke emissions and noncancer respiratory effects. Ann. Rev. Pub. Health **15**, 133–156 (1994)
30. Purohit, P., Tripathi, A.K., Kandpal, T.Ch.: Energetics of coal substitution by briquettes of agricultural residues. Energy **3**, 1321–1323 (2006)
31. Lehtikangas, P.: Storage effects on pelletised sawdust, logging residues and bark. Biomass Bioenergy **19**, 287–293 (2000)
32. ÖNORM M 7135: Compressed Wood or Compressed Bark in Natural State, Pellets and Briquettes, Requirements and Test Specifications. Österreichisches Normungsinstitut, Vienna, Austria (2000)
33. DIN 51731: Testing of Solid Fuels e Compressed Untreated Wood, Requirements and Testing. Deutsches Institut für Normung, Berlin, Germany (1996)
34. Peksa-Blanchard, M., Dolzan, P., Grassi, A., Heinimö, J., Junginger, M., Ranta, T., et al.: Global wood pellets markets and industry: policy drivers, market status and raw material potential. IEA Bioenergy Task 2007;40 [Online]. Avaiable at http://igitur-archive.library.uu.nl/chem/2008-0424-200431/UUindex.html [25/02/ 2012]
35. Uslu, A., Faaij, A.P.C., Bergman, P.C.A.: Pre-treatment technologies and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy **33**, 1206–1223 (2008)
36. Öhman, M., Boman, C., Hedman, H., Nordin, A., Boström, D.: Slagging tendencies of wood pellet ash during combustion in residential pellet burners. Biomass Bioenergy **2004**(27), 585–596 (2004)
37. Saastamoinen, J.J., Martti, J., Linna, L.: Simultaneous pyrolysis and char combustion. Fuel **72**, 599–609 (1993)
38. Mansaray, K.G., Ghaly, A.E.: Physical and thermochemical properties of rice husk. Energy Sources **19**, 989–1004 (1997)
39. Felfli, F.F.: Torrefaction Biomass, Technical Feasibility and Market Potential. Ph.D. Thesis. Faculty of Mechanical Engineering, State University of Campinas, Brazil (2003) (in Portuguese)
40. Felfli, F.F., Luengo, C.A., Soler, P.B.: Torrefaction biomass: features, applications and perspectives. In; Proceedings of the 3rd Meeting of Energy in Rural Areas, Campinas, SP, Brazil (2000)
41. Bergman, P.C.A., Boersma, A.R., Zwart, R.W.R., Kiel, J.H.A.: Torrefaction for Biomass Co-firing in Existing Coal-Fired Power Stations: Biocoal. ECN-C-05–013, Energy Research Center of the Netherlands, the Netherlands (2005)